AN INTRODUCTION TO THE DESIGN AND ALIGNMENT OF NAVIGATION CHANNELS

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1. Analytic Studies

1.1 Scope of the investigations pertinent to a navigation channel's project

The design of a navigation channel includes both the alignment of its plan and the dimensioning of its cross section. For a new channel, these two steps are to be considered after the necessity of its construction had been established and its geographical location had been decided upon. These primary decisions are usually the outcome of extensive economical and statistical studies of ship transport, beside the environmental conditions and requirements, with adequate foresight of the future prospects. For an existing channel, the same studies are carried with the intention of its development to meet the increasing present day needs and the future expectations. So, in both cases, such informations as numbers, sizes, and types of the expected vessels should have been known to the staff concerned. From this point of view, we presume that the following points are settled at that stage of the project:

(a) The characteristics of what could be called "Design Vessel". This might be a real existing or expected vessel; or a virtual one whose characteristics combine the optimums of the different vessels that would use the channel

(b) The characteristics of the expected traffic; namely, whether it is to be a one way traffic (i.e no ships encountering) or a double way traffic; and if double way, would it be for loaded ships in one direction and unloaded in the other ? Also, whether the traffic would allow ships overtaking or not. Other point in this respect is the extent of the "navigation control", and the quality of "navigation aids" in the channel.

The next step in the design programe, would be the assess of the following information about the existing or already determined geographical site:

(a) Meteorological and hydrodynamical informations; namely, the characteristics of the extreme predominant (or max. permissible by navigation regulations) characteristics of local winds, cunents, and waves.

(b) Geophysical informations; namely, topography and properties of bottom material.

With the above informations in hand, the technical design could be carried out, aiming at the fullfilment of the following demands:

(a) Adequately safe navigation of the "Design vessel" under the specified permissible environmental conditions, the intended type of traffic, and the available "navigation control" and "navigation aids". In fact, this is the main objective of the whole project.

(b) Keeping the channel's efficiency unaffected with time or with the minimum need for maintenance or repairs. The main item here is the possible deformation of an erodable channel's cross section, relative to its design geometry, that might necessitate periodical expensive dredging or the provision of some protective measures such as revetment or lining construction. This item is directly dependent upon the geophysical characteristics of the channel's site, its response to the hydrodynamic actions to which it would be subjected during the channel's service life. The possibility of repairs could arise whenever collisions, grounding, or impact with the embankments happen; which could be considered as partially dependent upon the available "navigation regulations", "navigation control", and "navigation aids".

These two demands form the guide lines of the whole quantitative design procedure, with its two main parts of: the cross section's dimensioning and the plan's alignment.

Concerning the cross section's dimensioning, the following items have to be evaluated:

(a) channel's width
(b) " depth
(c) " side slopes

Concerning the alignment of the channel's plan, the following items need to be evaluated:

(a) The minimum radius of a curve in the channel's plan

(b) The needed increase in channel's width along its curved width.

For we to be able to accomplish an adequate assess of these parameters, we need to analyse the behaviour of the design vessel when subjected to external environmental forces, while travelling through the navigation channel; its behaviour when travelling a curved channel reach; and whatever hydraulic phenomena might accompany its passage through the navigation channel's c.s. In the following, we shall attempt to do such analysis, separately, as this is the only possible means for handling such a complex problem comprehensively. However, it is to be noted that, the factors which influence the optimum design of the navigation channel are interrelated to each other; in such a way that a series of iteration and feed back processes are practically indespensible.

2 Straight Navigation Channels

2.1 Behaviour of a vessel when subjected to external environmental forces while travelling through a navigation channel

The environmental forces of interest here are those due to wind, currents, and waves. The response of the vessel to these forces is represented by its possible motions in the horzontal and the vertical planes. The horizontal motion of the vessel is effected by the transversal component of the wind, current, and waves to which it might be subjected. The vertical motion of the vessel is mainly due to waves and is periodic in nature, with an amplitude that would not exceed the amplitude of the wave or approximately half the waves height (heaving motion is the one of max. importance for our purpose, as it resemples the main cause for the ship to occupy greater depth than its draft) - see fig (1)

Concerning the horizontal motion of the vessel, the one of max. importance for our purpose is its sideways drift due to the collective transversal force of wind, cerents and waves. The action of this force on the mass of the vessel will cause it to displace from the channel's center line by a certain velocity U_t. This transversal velocity will be compensated by steering the vessel with an imcreased speed with its center line enclined to that of the channel by an angle θ towards the transversal force. The angle θ which could be referred to as the angle of "intended yaw" is related to the vessel's speed V along the channel's center line, and the sideways drifting speed U_t of the external forces by:

$$\theta = \tan^{-1} \frac{U_t}{V} \qquad (2.1)$$

The passage of ship through the channel's c.s. while in such tilted position let her occupy more space than its beam width b, fig (2). It is very clear, from the geometry of fig. (2) that the excess in the occupied space of the ship b_{y_1} is equal to:

$$b_{y_1} = \ell \sin\theta + b\,(\cos\theta - 1) \qquad (2.2)$$

or

$$\frac{b_{y_1}}{b} = \frac{\ell}{b} \sin\theta + (\cos\theta - 1) \qquad (2.3)$$

where ℓ, b are the length and breadth, respectively of the vessel.

It is thus clear that an estimation of the drifting velocity U_t would lead to an estimation of the minimum width of the "manoevering lane" that is needed by a specific vessel to pass along a straight reach of a navigation channel. It is to be noted that the formulas (2.2) and (2.3) are derived for a case where the vessel's center of gyration is at its mid length. Anyway, knowing the exact center of gyration would lead to similar relations, while our ossumption leads to the minimum b_y.

The calculations that lead to estimating U_t are rather complicated and needs much bigger space than what we can provide without distraying our attention from the main subject.

2.2 <u>Involuntary yaw</u>:

This involuntary deviation of the ship's center line from that of the channel's center line is due to the practical impossibility of keeping the vessel's orientation constant with time. The amount of the involuntary yaw is a characteristic of the considered vessel's controllability and pilotage; and is measured by what is called "the critical angle of deviation" α from the track of the vessel (i.e. the channel's or the manoevering lane's center line). see fig. (3).

At the critical angle α, the vessel's rudder angle is set in a corrective setting to restore its initial orientation. The value of α depends on whether the orientation adjustment operation is done manually or automatically. The following values of α are meant to give an idea about its order of magnitude:

α = 0.05 to 0.07 radians for manually operated ships

α = 0.02 radians for automatically operated ships

An analysis of the corrective operation is shown in fig. (3), from which it is assumed that the ship will continue its forward straight line course (being deviated by α from the correct course) before it starts turning; and after the setting up of the correcting rudder angle. As there is no sideway drift in this analysis, then, the ship will continue this deviated straight line (along its center line) motion with its speed $\bar{V}$ and for a time t_1. At the end of that time, the ship starts turning, and thus decreasing its angle of deviation until its centre line is parallel to its correct track where the angle of deviation is Zero. This turning time is supposed to be t_2, and assuming a linear decrease of α, then its mean value during the time period t_2 is $\frac{\alpha}{2}$. Fig. (3) illustrates this manoever, from which the following formula is derived:

$$b_{y_2} = \alpha \bar{V} (t_1 + t_2) \qquad \text{(2.4)}$$

where

$\bar{V}$ = vessel's velocity along its longitudinal center line in this case $\bar{V}$ is the same as V of Eqn. (2.1)

α = critical angle of deviation

t_1 = time of progress in the straight deviated course

t_2 = turning time till restoration of the correct orientation

b_{y_2} = the excess in the occupied space of the ship due to involuntary yaw

In the above analysis, the values of t_1 and t_2 are characteristics of the ship's controllability and pilotage. The following values of t_1 and t_2 (for river ships) are meant to give an idea about their order of magnitude:

$$t_1 = 10 \text{ to } 15 \text{ sec.}^s$$
$$t_2 = 20 \text{ to } 30 \text{ sec.}^s$$

We should notice that the value of b_{y_2} could be calculated directly from equation (2.2), by substituting α for θ. In such case we are simply neglecting the assumed detailed correcting manoever with its time components t_1 and t_2. We can add here that the value of b_{y_2}, as calculated from (2.4) would be of practical interest, if its value is more than that obtained from (2.2) by substituting α for θ.

For the purpose of determining the minimum needed width of the manoevering lane in a straight reach of the navigation channel; where a lateral drift U_t is expected, we have to take into consideration both b_{y_1} and b_{y_2}. This point, and the fact that there is practically a maximum limit for the range of the vessel's rudder angle (normally 35^o); let us think of determining the maximum possible value of θ in (2.1); taking into account the max value of α (can be 8^o), and an emergency reserve (usually 10^o). This max. θ could be formulated by:

$$\theta_{max} = 35^o - (\alpha + 10^o)$$

This max. possible value of θ could put a limit to the max. permissible value of U_t, when V is prescribed. In other words there could be a certain limiting environmental conditions, beyond which the navigation in the channel should be prohibited or re-regulated in accordance with the intensity of the environmental conditions and their corresponding drifting velocity U_t.

From the above, it is possible to evaluate the minimum needed width of the design vessel's manoevering lane B_m, when navigating through a straight channel, while subjected to a lateral drifting U_t that is effected by whatever expected (or permissible) environmental forces. This very important parameter of the navigation channel's project; forms the fundamental component of th total channel's width (measured at the channel's bottom); which could be sub-divided into the following parts: see fig. (4)

(a) The manoevering-lane's width B_m
(b) The ship clearance lane's width B_s
(in cases of double way channels)
(c) The bank-clearance lane's width B_b

The evaluation of the last two parts would be possible after the following analysis of the hydraulic phenomena, that are created by the passing ship in the navigation channel's c.s.

2.3 Ship- created hydraulic phenomena, in a navigation channel's cross section

While a navigation channel's cross section can be restricted (inland navigation channels) or partially restricted (coastal channel's and harbour's approaches), or even unresticted (open sea channels); see fig (4); the following analysis applies only to the case of a restricted channel. However, a partially restricted channel could be treated (from point of view of the ship-created hydraulic phenomena) as a restricted channel whose cross section could be easily calculated as in fig. (5).

When a ship moves through a restricted navigable waterway, the water immediatly in front of it will have to make room for the ship's body, whereas water has to be supplies immediatly behind it to fill the void that had been occupied by the body of the moving ship. Thus, a return current, alongside and underneath the ship, is generated whose velocity results in the lowering of the water level in the ship's vicinity.

The return current phenomena might have a practical damaging effect on an erodable cross section, while the lowering of the water level is one of the major factors contributing to the "squat" of the vessel or the sinking of the ships keel below its standstill draft level, thus influencing the needed water depth of the channel's cross section.

Moreover, there is a pattern of waves that accompany the passage of the ship, whose practical influence on the design of an erodable channel's c.s, and the protective structure of its embankments; is to be taken into account. This wave phenomenon follows the configurations of the water pressure around the ship's hull. For two dimensional flow of an inviscid fluid around a ship's hull, the pressure will be greater than the average at he ship's mid length region; while aft from the bow the pressure goes from positive to negative and towards the stren from negative to positive. The excess pressure will cause the water surface to rise and maintain dynamic equilibrium, but the developed kinetic energy causes the generation of a wave train. The resulting wave pattern consists of diverging waves and transverse waves, see fig (6). These waves form a constant pattern and meet to form a locus of cusps at an angle to the track of the moving hull. In deep water this angle is about 19^{o} 28`, and becomes greater in shallow water.

In the following we shall introduce one of the availabe (and still under investigation) methods of calculating the ship - created hydraulic phenomena; namely; return current U, depression in water level Z, and ship waves height H.

(a) Return current and depression in water level after Schiff and Jansen (1953):

The problem was studied, while making the following assumptions:

1- Constant ship speed V in a canal of uniform rectangular c.s

2- Straight canal with infinite length

3- Uniform ship c.s., i.e. neglecting end effects

4- Uniform velocity of the return current all around the ship

5- Friction losses are neglected

6- The squat is the same as the depression in water level, and thus presumed to be the same all along the ship's length

Considering a system of exese mounted over the ship that travels at the constant speed V, and the equations of energy and continnity at two sections of the canal; one encluding the ship and the other excluding it, we have:

$$\frac{V^2}{2g} = \frac{(V + U)^2}{2g} Z \qquad (2.5)$$

$$VF = (F - f - BZ)(V + u) \qquad (2.6)$$

where:

f = the submerged cross sectional area of the vessel

F = cross sectional area of the channel

B = the channel's width

Z = the depression of water level

V = the velocity of water in the cross section that excludes the ship relative to the moving axese. For the case of no currents in the channel, V = the ship's velocity

U = the velocity of the return current, thus (V+U) is the water velocity alongside the ship, i.e in the channel's c. s that includes the ship.

These two equations were put in a dimensionless form relating $\frac{Z}{h_1}$ and $\frac{U}{\sqrt{g\ h_1}}$ respectively with $\frac{f}{F}$ and $\frac{V}{\sqrt{g\ h_1}}$; and were plotted in two sets of curves - fig, (7) and fig. (8) where h_1 is the mean depth of the channel, and in applying the above equations (or their graphical solutions) for trapezoidal cross section renders $h_1 = \frac{F}{B_u}$, where B_u is the width at the water surface.

It has been also proved mathematically, and confirmed by both field and laboratory observations, the existence of what is called "limiting speed" V_1, which could not be exceeded by any self propelled vessel. Any increase in the vessel's power-output at this limiting speed will result in an increased turbulence at the stern of the vessel without any significant increase in the speed. The dimensionless relations between $\frac{V_1}{\sqrt{g\ h_1}}$ and $\frac{f}{F}$ together with the corresponding limiting values of $\frac{Z}{h_1}$ and $\frac{u}{\sqrt{gh_1}}$ are plotted in fig. (9).

However, both field and laboratory observations showed that the depression of the water level, and consequently the sinkage of the ship's body or "squat", is not the same along the ship's length; being greater at the stern of a self-propelled ship. The local influence of the propeller on the flow pattern was reasoned as the cause of this phenomenon.

Moreover, field and laboratory observations show that the depression of water leve, and the velocity of the return current, are not uniform over the entire width of the channel; both being greater near the ship's body and lesser near to the channel's banks. This deviation from the assumed uniform distribution of the water level's depression and the return current's velocity was also found to increase with the increase in ship's velocity; even in cases of towed ships.

All these observational results lead to the following recommendations for calculating the amounts of water level's depression Z (or squat) and the return current's velocity U:

(a) Values as deduced from the graphs, are to be multiplied by a factor of 1.0 to 1.4, to get the actual values near the banks (the exact factor increases with the ships speed)

(b) Values as deduced from the graphs, are to be multiplied by a factor of 1.2 to 1.6 to get the actual values near the ship

(c) To get the maximum depression of water level at the ship's stern, the value got from (b) above has to be distributed along the ship's length such that the value at the stern is 40 % higher than that at the bow.

The actual distribution of the hydraulic energy in the channel's c.s, is very important when we attempt to analyse the case of a ship that has to deviate from the channel's center line during its trip (due to encountering or overtaking other ships).

(b) <u>Ship waves height, both at the vicinity of the ship "H_s" and in the vicinity of the channel's embankment "H_b", after Balamin and Bykov (1965)</u>:

$$H_s = \frac{V^2}{2g}\left[2.5\left[1 - \left(1 - \frac{1}{\sqrt{4.2 + \frac{F}{f}}}\right)\left(\frac{\frac{F}{f} - 1}{\frac{F}{f}}\right)^2\right]\right] \qquad 2.7)$$

$$H_b = \frac{2 + \left(\frac{B_u}{l}\right)^{1/2}}{1 + \left(\frac{B_u}{l}\right)^{1/2}} \cdot H_s \qquad 2.8)$$

where B_u and l are the channel's width at the surface, and the ship's length, respectively; all other notations as given before.

The phenomenon of ship-created waves is the outcome of the other two phenomena; and thus, subjected to the influence of the same factors that effect them. A lot of investigations were carried to check the changes in the ship waves characteristics with the distance from the sailing line (i.e the channel's center line); and when they propagate over different side slopes and composite side slopes (e.g with berms). In all these studies it is presumed that the celerity of the waves is equal to the speed of the ship, which is also confirmed by observations.

The importance of ship waves investigations has bearing on the damaging action of the waves, either on the channel's embankments or to unobserving users of the shoreline beaches

2.4 Deviation of the ship's course from the channel's Center line

Even with the assumptions's of Schiff and Jensen, an exact mathematical analysis of the problem is too complicated to be presented here. But, it is possible to analyse the situation for the purpose of having a qualitatite illustration of its outcomes.

The ship's cross section, being closer to one of the channel's sides, would contract one of the side streams of the return current and enlarge the other, fig (19). Relating to the case of symmetrical flow of the return current (ship's course along the channel's center line), and assuming the same discharge through each of the two side streams, we can deduce that the return current velocity will be more in the narrower stream than in the case of symmetrical flow, and less in the wider stream. Consequently, the drop in the water level will be more in the narrower stream than for the case of a symmetrical flow, and less in the wider stream. A rough evaluation of the values of the depressions in the water level at both sides of the ship can be got by multiplying the value for a symmetrical course by the ratio between the cross sectional areas of the two side streams. For a constant water depth, this would, simply, be the ratio between the widths of the two side streams, or $\frac{B-b+\nabla}{B-b-\nabla}$ for the narrower stream, and $\frac{B-b-\nabla}{B-b+\nabla}$ for the wider stream, where ∇ is the ship course's deviation from the center line of the channel's cross section.

Moreover, we noted before that the depression in water level is not the same along the ships length, being about 40 % more at the stern. Thus, considering the hydrostatic forces due to the distribution of the water level along the two sides of the, equally squatted, body of the ship; we can identify: -

1- A drifting force towards the nearest bank
2- A rotational moment, tending to turn the ship towards the channel's center line.

The influence of these actions on the ship's controllability should, by then, be clear; together with its implications on the channel's width (namely, the bank-clearance lane B_b).

An accepted recommendation for the evaluation of the bank-clearance lane, is based upon the case of a ship that sails along the boundary limit of the manoevering lane; and a thumb rule principle is to have a bank-clearance lane width B_b, at least equal to the Design Vessel's beam b.

For we to be able to estimate the needed width of the ship-clearance lane B_s; we shall discuss, in the following, the behaviour of the vessel during the encountering and overtaking manoevers. We can note that, in such cases, the ships are compelled to deviate from the channel's center line. The hydrodynamic conditions in such situations are extremely complicated and rapidly changing, which render them rather formidable to quantitative. analysis.

(a) Encountering Manoever:

The two flow patterns, of the two ships, partly annihilate each other, in this case. Also, because of the short duration of the event, the difficulties experienced by the ships due to the actions of transverse forces and longitudinal torques are relatively easy to overcome, provided that there is sufficient room. The greater danger for encountering ships is caused by the fact that the torque, which tends to deviate the ship from her course, changes direction several times during the manoever, (in a narrow canal only an experienced and vigilant steerman is able to keep his ship under control if the manoever is excuted at a fairly high speed). The varying play of forces during the encounter, as well as overtaking, constitutes a second cause for what is called: "sheering out of line". This is especially dangerous when in busy traffic immediatly after encounter the ship is forced to go through the manoever a second time, e.g. when encountering a tug with towed convoy..

Here; it should also be realized how important is an appropriate navigation regulations and control, as the intensity of the forces and torques that would act on the ships depends strongly on their speeds; and hencefore, the danger of accidents in cases of encounters can be eliminated by slowing down in due time.

(b) Overtaking manoever:

Both the waves and currents systems of the two ships reinforce each other in this case. Particularly when the difference in speeds is small the two ships keep running alongside for a long time; thus, the hydrostatic forces have time enough to work their influence. This is the more so, because the overtaking ship is slowed down automatically, while the retarding influence on it is accompanied by an accelerating action on the ship being overtaken. For the sake of safety, it is therefore desirable that the slower ship (i.e the one to be overtaken), facilitates the manoever by slowing down still more. In many cases, this is even necessary to make overtaking possible at all.

3. Curved Navigation Channels

From the navigational point of view, the channel's plan ought to be:

(a) Reasonably straight
(b) Without S curves
(c) At right angles to the shoreline, or in the direction of the prevailing storm wind.

However, the local conditions, together with the economy of the channel's construction and/or maintenance might imply deviations from the above basic principles. Aside from the specific reasons that might justify a certain plan for the proposed waterway, there should be a limit for the amount of deviation from the ideal requirements; such that the navigation through the channel is not seriously affected. Our previous analysis showed the influence of the channel's orientation, relative to the local hydrodynamic phenomena, on the adequate dimensionning of its width, to ensure navigation safety. In the following we shall study the influenece of a curved plan, and the ultimate allowable curvature; together with whatever implications on the channel's width.

An analysis of the ship's behaviour over a curved course; would serve in giving deeper insight in the problem and its implications:

3.1 Ship's behaviour over a curved Course

The motion of the ship along a curved course is too complicated, that it is necessary to introduce simplifying assumptions as follows:

1. The vessel is assumed to move in an infinite body of water and in a straight line course, then at a certain instant t, its rudder is set at certain constant angle γ relative to its longitudinal axis.
2. The center of gravity of the vessel will, then, start tracing a curve, whose radius of curvature decreases gradually, tending to a certain limiting value R.
3. After an infinite time, the vessel's course would be a circle of radius R; which in practice this condition will be reached, with a negligible deviation, after a rather short time. We suppose that this stage of the manoever is reached, and thus, we shall study the vessel's equilibrium while its center of gravity is describing a circle of radius R. fig (10).

Analysing the forces in the direction of the tangent to the circle of curvature and the normal to it, we get the following two equations of motions, in these two directions, respectively:

$$F_1 \cos\epsilon - F_2 \sin(\gamma - \epsilon) - AV^2 \cos^3\epsilon - BV^2 \sin^2\epsilon =$$

$$= m\frac{dv}{dt} = 0 \text{ (if we assume V to be constant) } \text{-------} \quad 3,1)$$

$$- F_1 \sin\epsilon + F_2 \cos(\gamma - \epsilon) + AV^2 \cos^2\epsilon \sin\epsilon -$$

$$BV^2 \cos\epsilon \sin^2\epsilon \quad = - m\frac{V^2}{R} \text{------------------------} \quad 3.2)$$

where:

F_1 = the vessel's force of propulsion, along its axis

F_2 = the force over the rudder, acting normal to its surface S

AV^2= the resistance to the ship's tractive force, acting along its axis and in opposite direction to F_1. We note here that this force is the one calculated from Gebers-Engels formula (namely $AV_r^{2.25}$), as modified for our conditions of motion in an infinite body of water.

BV^2= the impact on the vessel's side together with all frictional resistance, acting in a direction normal to the vessel's axis

γ = the rudder angle

ϵ = the angle of yaw of the vessel, during the manoever, namely the one between its axis and the tangent to the circle of curvature.

R = radius of the circle of curvature

Multiflying 3.1) by $\sin\epsilon$, and 3.2) by $\cos\epsilon$, and adding, we eliminate F_1 and AV^2, getting

$$F_2 \cos\gamma - BV^2 \sin^2\epsilon + m\frac{V^2}{R}\cos\epsilon = 0 \text{----------} \quad 3.3)$$

ϵ is normally too small, that $\cos\epsilon$ could be put equal to 1,0.

$$\therefore F_2 \cos\gamma - BV^2 \sin^2\epsilon + m\frac{V^2}{R} = 0 \quad \text{------------------ } 3.4)$$

For the rotational motion, the equation of equilibrium is:

$$I\frac{d\omega}{dt} = C_m - C_r \quad \text{------------------------------ } 3.5)$$

where:

C_m = The moment of F_2 around the axis of rotation, through the center of gravity

C_r = the moment of the reaction force around the same axis

I = the moment of inertia of the vessel about the vertical axis through its center of gravity

ω = angular velocity = $\dfrac{V}{R}$

for V = const. $\quad \therefore \omega$ = const. $\quad$ and $\dfrac{d\omega}{dt} = 0$

$\therefore$ 3.5) reduces to:

$$0 = C_m - C_r \quad \text{------------------------------ } 3.6)$$

$$\therefore C_m = C_r$$

Assuming the center of gravity to be at mid length:

$$\therefore C_m = \frac{F_2 \, l}{2} \cdot \cos\gamma$$

C_r is due to the force of impact on the vessel's side together with frictional resistance at the prow and stern, the latter is negligiby small compared with the former.

The value of C_r is given by:

$$C_r = 3.13 \, d \, \omega^2 \, l^4$$

$\therefore$ Equation 3.6) is:

$$\frac{F_2\ l}{2} \cos \gamma = 3{,}13\ l^4\ d\ \omega^2$$

substituting $\frac{V}{R}$ for ω, we get:

$$F_2 \cos \gamma = \frac{6{,}26\ l^3\ dv^2}{R^2} \qquad \text{-------------------- } 3.7)$$

3.2 Evaluating the minimum value of the bends radius of curvature

Once more, considering the force BV^2, the term B can be put as equal to $B' + B''$ where B' corresponds to the impact on the lateral sides of the vessel, and B'' to the friction on the bottom, prow, and stern.

After Hütte, $B' = K'\ l\ d$

where $K' = \frac{\phi\ \gamma_w}{2\ g} = \frac{\gamma_w}{g}$ for $\phi = 2$ $\qquad$ γ_w = sea waters specific gravity in kgm/m^3

$= 101{,}94$

$\therefore B' = 101{,}94\ l\ d$

The value of B'' can be given by: $0{,}15\ l\ b$

$\therefore B = 101{,}94\ l\ d + 0{,}15\ l\ b$

As we said before, B'' could be neglected, in comparison with B', therefore:

$$B = 101{,}94\ l\ d \qquad \text{--------------------------- } 3.8)$$

Substituting for F_2 as in equation 3.7) and for B as in equation 3.8), in equation 3.4), we finally get:

$$\sin \epsilon = \sqrt{0{,}0626\ \frac{l^2}{R^2} + 1{,}0194\ \frac{b}{R}} \qquad \text{------------ } 3.9)$$

The angle γ is a function of the vessel's dimensions, the area of the rudder S, and the yaw of the vessel, i.e. ϵ

Van Gauwenberge gave the following relation for it:

$$R = \frac{\mu}{4 \sin\gamma \sqrt{\cos\gamma}} \cdot \sqrt{\frac{l^3 d}{S}} \quad \text{-------------} 3.10)$$

where μ is a coefficient > 1 to do for the influence of the yaw.

We can take $\mu = \frac{1}{\cos \epsilon}$, where ϵ is as given by 3.9).

The area of rudder is between o,02 l d and 0,03 l d, thus, $\sqrt{\frac{l\ d}{S}}$ varies between 7,07 and 5,75.

Equation 3.10) can be reduced to:

$$R = \sqrt{\frac{l\ d}{S}} \cdot \frac{\mu}{4 \sin\gamma \sqrt{\cos\gamma}} \cdot l$$

$$R = \sqrt{\frac{l\ d}{S}} \cdot K_0 \cdot l \quad \text{-----------------------} 3.11)$$

as we mentioned above, $\sqrt{\frac{l\ d}{S}}$ varies between 7,07 and 5.75, while K_0 depends on γ and ϵ (Van Gauwenberge, while mentioning that the value of K_0 is to be got by experiense, suggests a minimum value of it equal to 1,7, and this, in turn, leads to the oftenly repeated rule of taking the minimum R = 10 l. In our opinion, this value is too high).

To get the value of K_0, we suggest to take a value of

$\gamma = 25^o$ (as the normal range of the rudder angle is 35^o, and leaving 10^o for emergency), then $4 \sin\gamma \cdot \sqrt{\cos\gamma} = 1,6$. The value of e is too small to justify taking $\mu = 1$, and this leads to $K_0 = 0,625$.

∴ The value of R can be, ultimately equal to 0,625 x 7,07 l or 0,625 x 5,75 l depending upon the area of the vessel's rudder i.e. R can be equal to 3,59 l up to 4,42 l in the extreme, according to the area of the rudder.

The above analysis leads to the implications concerning the value of the radius of curvature of any curved reach of the navigation channel. However, it should be put in mind, that the bigger the value of R, the smaller the value of γ, within the normal practical range, and consequently the smoother and safer is the turning manoever. Another point should be also put in mind when planning the channel's aligment, namely, that the vessel takes time before assuming the above mentioned conditions of circular turn, as its turning angle increases gradually starting from zero at the instant when the rudder is set at its angle γ. This shows the importance of providing for a transition curve between the circular curve and the straight course preceding and following it. Another word is to be said about this turning manoever, and that it necessitates a slow down in the vessel's velocity due to the surplus resistance it meets along the curve, as compared to a straight line course. Thus, all the implications that result from that should be put in mind when dimensioning the channel's cross section at the bend. Sometimes, it is also necessary to take into account what we can call the "sight distance", defined as the minimum distance ahead of the vessel that should be clear in front of the pilot. Normally, a distance of one mile is demanded, and the influence of this distance on dimensioning the proposed bends is analogical to the case of highway design, which is given in fig. 12). However we should not forget that a clear "sight distance" ahead of the pilot is subject to the weather conditions, and the spotting of the vessels during their travel along the channel (from some central office), would have a big influence on the safety of the navigation and the control of the traffic. Here, again this new factor can be of considerable weight in the alignment of the channel's bends depending upon the accuracy and reliability of this operation.

3.3 The enlargement of the channel's width at bends

The next point concerning the design of the channel's bends concerns with the enlargement of the channel's width, to do for the deviation of the ship's beam from the normal to the channel's axis. Simple geometrical calculation shows that the ship over a bend, occupies a width $\frac{l^2}{4R}$ bigger that its width (fig. 13). Anyway, this is considered to be too little, and some authors suggest a value 4 times as much per each manoevering lane.

Concerning the design of bends, and especially the above considered value of the minimum radius of curvature, we draw the attention to the influence of the intended yaw that might be needed, in certain weather conditions in reducing the value of possible γ. In other words if the situation is such that a very small R (as for ex. the one corresponding to $\gamma = 25^{o}$) is to be adopted, then this will have consequences on the impossibility of crossing the bend, beyond certain weather conditions, in the least a double way traffic might not be possible then. Such limiting weather conditions could be known by knowing the value of the intended yaw that is kept within the range of the rudder angle to do for them. This point is the one we mentioned in detail when treating the design of the manoevring lane's width.

3.4 Some of the empirical rules for designing navigation channels bends

It is interesting to end this study by some of the several empirical rules for the design of navigation channel's bends. These we enlist as follows:

1. Miranda (1926) gave the following rule of thumb for the value of R, and for ship's speeds between 8 and 10 miles/h:
   a) if the change in course, has an inner angle $> 155^{o}$; $R \nless 3\,l$
   b) if the change in course has an inner angle between 145^{o} and 155^{o}; $R \nless 5\,l$
   c) if the change in course has an inner angle $< 145^{o}$; $R \nless 10\,l$

2. $x = 4\left[R - \sqrt{R^2 - (\frac{1^2}{4})}\right]$ ---------------------- 3.12)

3. $x = \frac{1^2}{2R^2}$ ---------------------- 3.13)

4. $x = \left[\sqrt{R^2 + (2\,1\,)^2}\right] - (R + \frac{b}{2})$ ------------- 3.14)

where x = the increase of the channel's width over the bend.

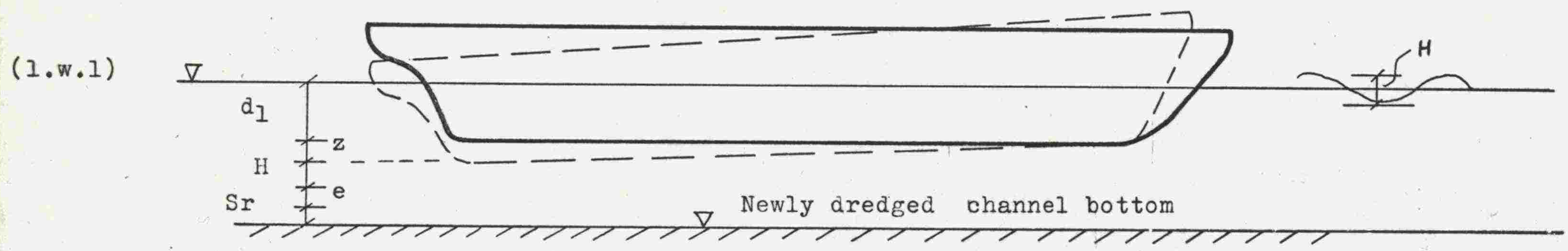
5. The Suez Canal Research Center conducted an investigation for establishing a relation between R, 1 and x. It was assumed that the ship's center of gyration is located at $\frac{1}{4}$ from the stern, and experience in the Suez Canal showed that there should be a distance 1 from the bow of the ship to the canal side in the plane of its keel. From fig. 14) it is simple to deduce the following relation:

$$(R + \frac{B + x}{2})^2 = (\frac{7}{4}\,1)^2 + R^2$$

and solving for R we get:

$$R = \frac{1}{(B+x)}\left[3{,}06\ \ 1^2 - \frac{(B+x)^2}{4}\right] \quad \text{-------------------- 3.15)}$$

Components of design depth of navigation channel



d_1 = loaded draft of design ship

Z = squat (assumed equal to max depression in wl at stern)

H = expected heaving motion = H/2

e = under keel clearence or foot of the pilot

$\simeq$ 60cm for soft mud bottom

$\simeq$ 120cm for hard material bottom

Sr = a reserve of expected rise in water level, due to sedimentation, in the time period between 2 successive dredges

NOTES: 1 - The reference water level (i.e l.w.l) depends on range of tides and nature and timing of traffic

2 - The wave height H depends on allowable extrewe locol waves and navigation regulations

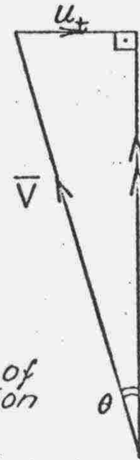
fig (1)

Increase in Monœvring-lane's width, by, due to yawning, either intended or involuntary

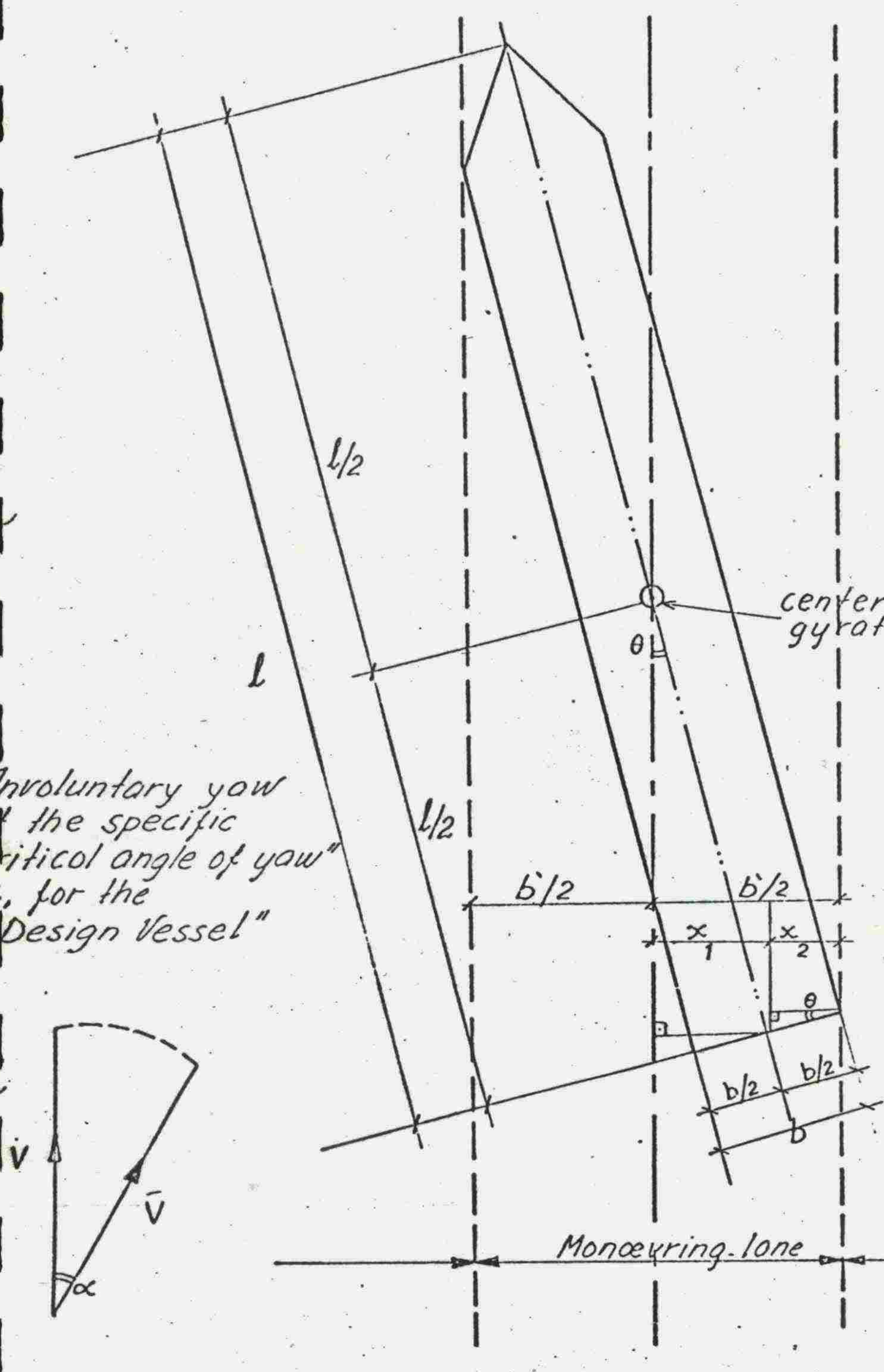
$\dot{U}$ ≡ Max. Velocity of Lateral drift

$\bar{V}$ ≡ Vessel's Velocity along its center-line

V ≡ Vessel's Velocity along Monœvring Lane's center-line



Involuntary yaw ≤ the specific "critical angle of yaw" α, for the "Design Vessel"



Note:

Position of the Vessel's center of gyration could be different.

$$x_1 = \frac{l}{2} \sin\theta$$

$$x_2 = \frac{b}{2} \cos\theta$$

$$\frac{b'}{2} = x_1 + x_2 = \frac{1}{2}(l \sin\theta + b \cos\theta)$$

$$b' = l \sin\theta + b\cos\theta$$

$$b' - b = l\sin\theta + b(\cos\theta - 1) = by$$

$$\frac{by}{b} = \frac{l}{b}\sin\theta + (\cos\theta - 1)$$

θ ≡ angle of yaw

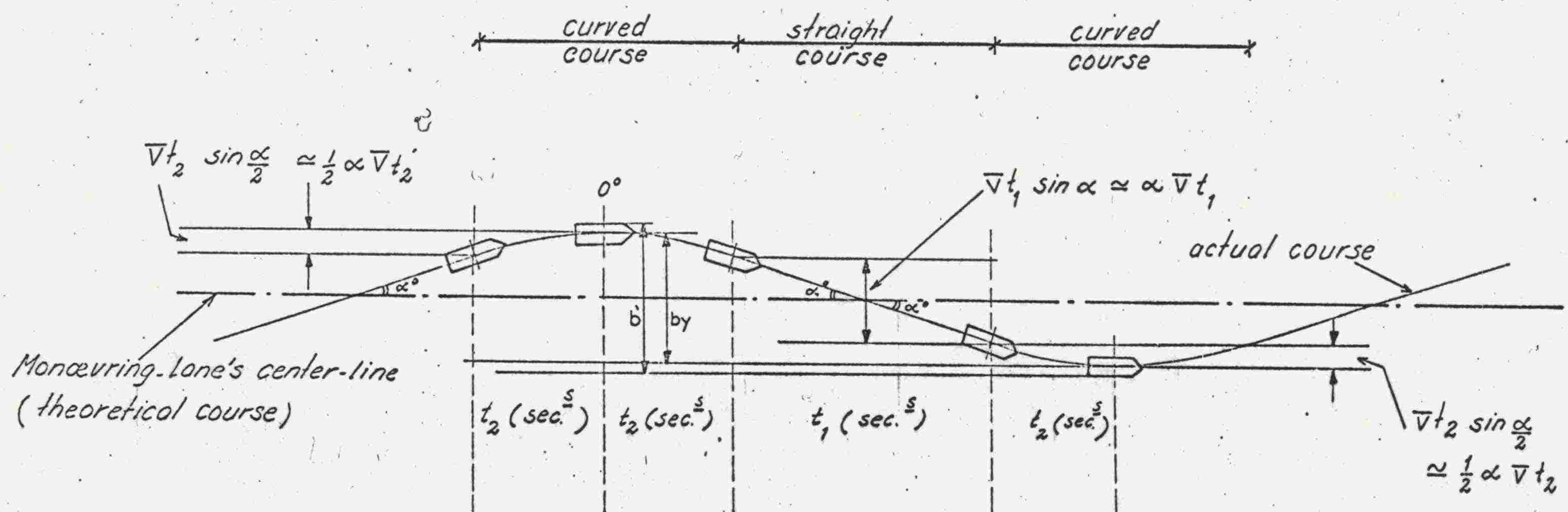
l ≡ Design Vessel's length

b ≡ " " beam

fig (2)

Increase in monœvring lane's width "by" due to involuntary yawning.

(exaggerated scale)



$b' = \alpha\overline{V}(t_1+t_2) + b = \alpha\overline{V}t + b$

$by = \alpha\overline{V}(t_1+t_2) = \alpha\overline{V}t = b' - b$

$t = t_1 + t_2$

α = critical angle of devition from the theoretical coure

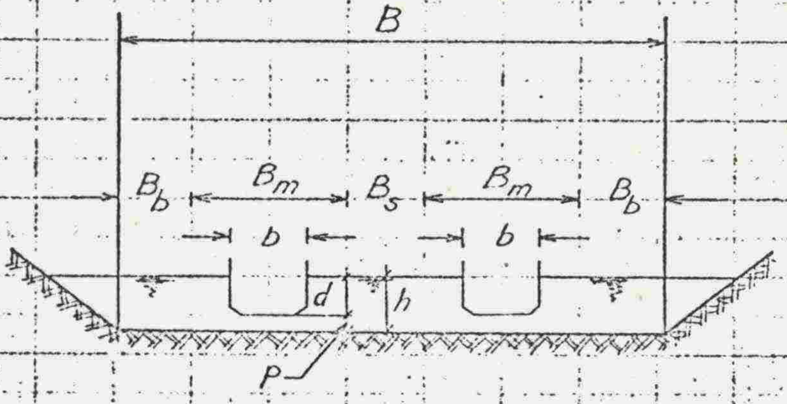
$\overline{V}$ = Design Vessel's Velocity

t_1 = progress time in the straight deviated course

t_2 = time for re-orientation parallel to the theoritical course

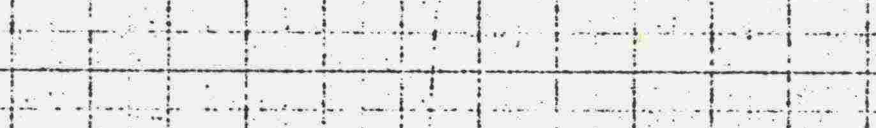
fig. (3)

: Notations - and types of channel's c.s



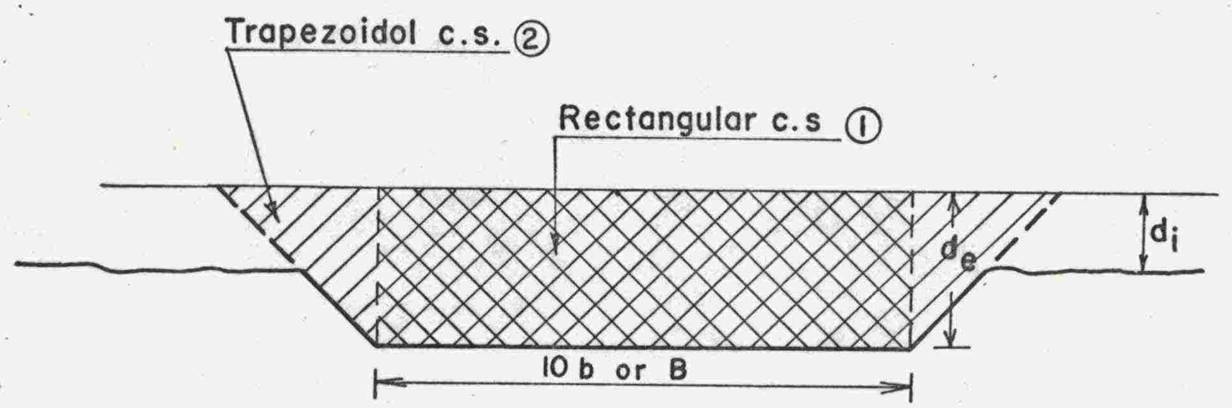
restricted c.s.

Partially restricted c.s.



Unrestricted Waterway

fig. (4)



b = beam of design ship

a

d_i = initiol water depht

d_e = excavated water depth

B = widht of channel's c.s.

Hydraulic phenomena ≡ return current U and depression in waterlevel Z

Phenomena = (phenomena in c.s. $F_{①}$ + phenomena in c.s. $F_{②}$) $\times \frac{1}{2}\frac{d_e}{d_i}$

Ship - created hydraulic phenomena in navigation channel's c.s. of the "partially restricted type"

fig. (5)

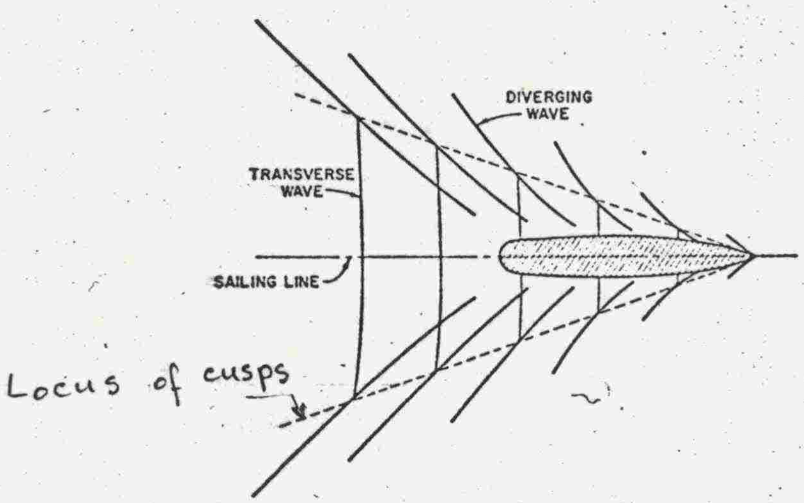

DIVERGING WAVE
TRANSVERSE WAVE
SAILING LINE
Locus of cusps

fig. (6)

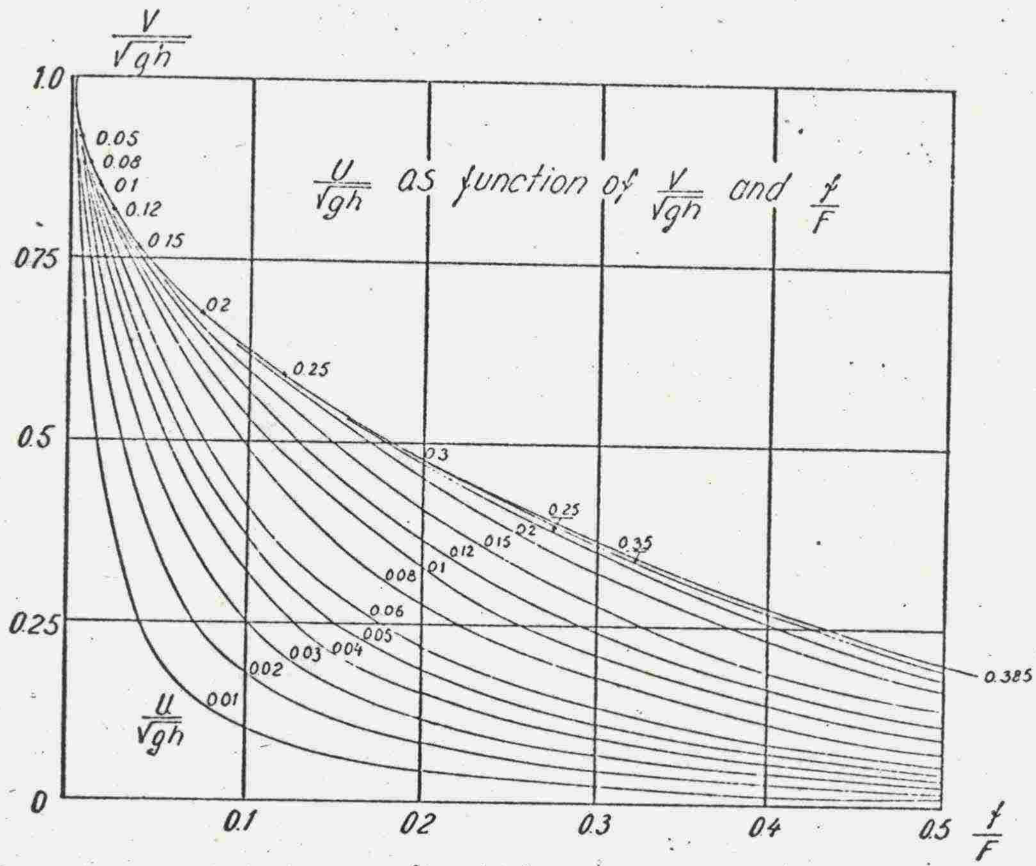

$\frac{V}{\sqrt{gh}}$
$\frac{U}{\sqrt{gh}}$ as function of $\frac{V}{\sqrt{gh}}$ and $\frac{f}{F}$
1.0
0.75
0.5
0.25
0
0.1
0.2
0.3
0.4
0.5
$\frac{f}{F}$
0.05
0.08
0.1
0.12
0.15
0.2
0.25
0.3
0.35
0.385
0.01
0.02
0.03
0.04
0.05
0.06
0.08
$\frac{U}{\sqrt{gh}}$

fig. (7)

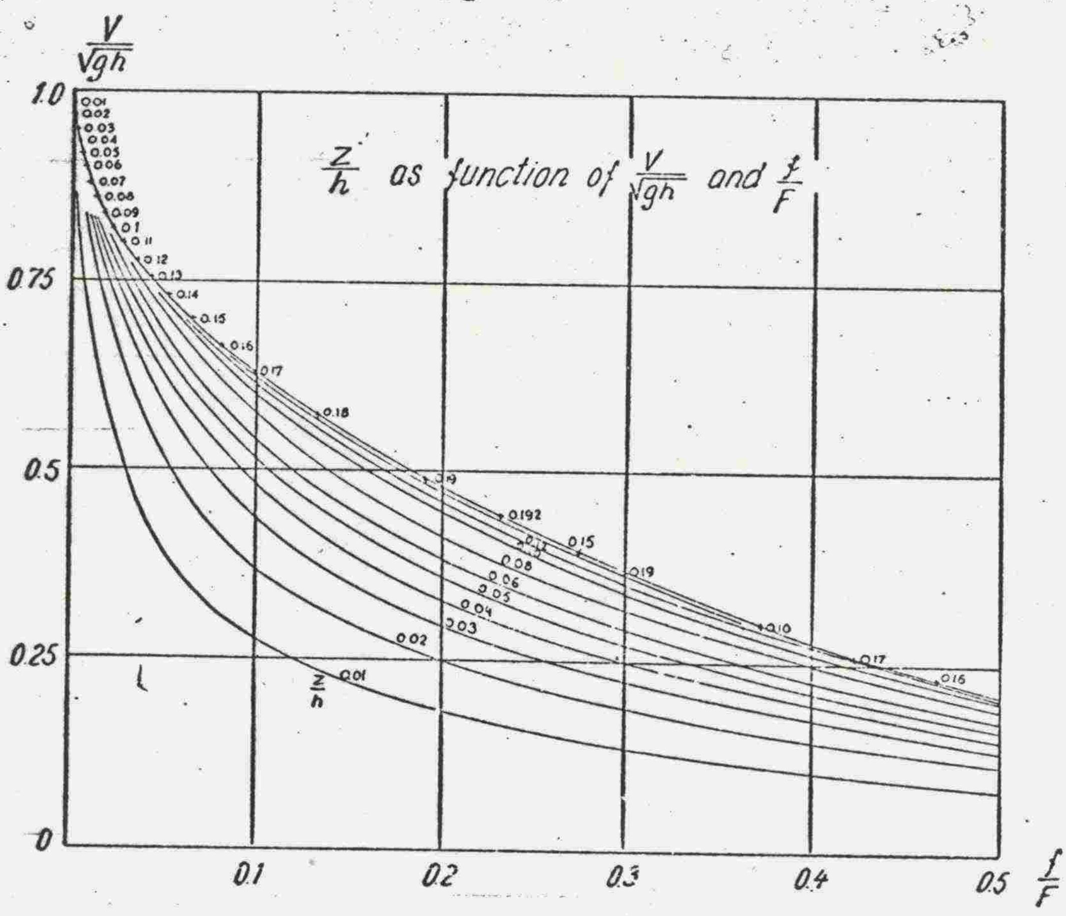

$\frac{V}{\sqrt{gh}}$
$\frac{Z}{h}$ as function of $\frac{V}{\sqrt{gh}}$ and $\frac{f}{F}$
1.0
0.75
0.5
0.25
0
0.1
0.2
0.3
0.4
0.5
$\frac{f}{F}$
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1
0.11
0.12
0.13
0.14
0.15
0.16
0.17
0.18
0.19
0.192
0.10
0.16
$\frac{Z}{h}$

fig. (8)

Schijf's $\frac{V_l}{\sqrt{gh}}$ and associated $\frac{U}{\sqrt{gh}}$ and $\frac{Z}{h}$ as function of $\frac{f}{F}$

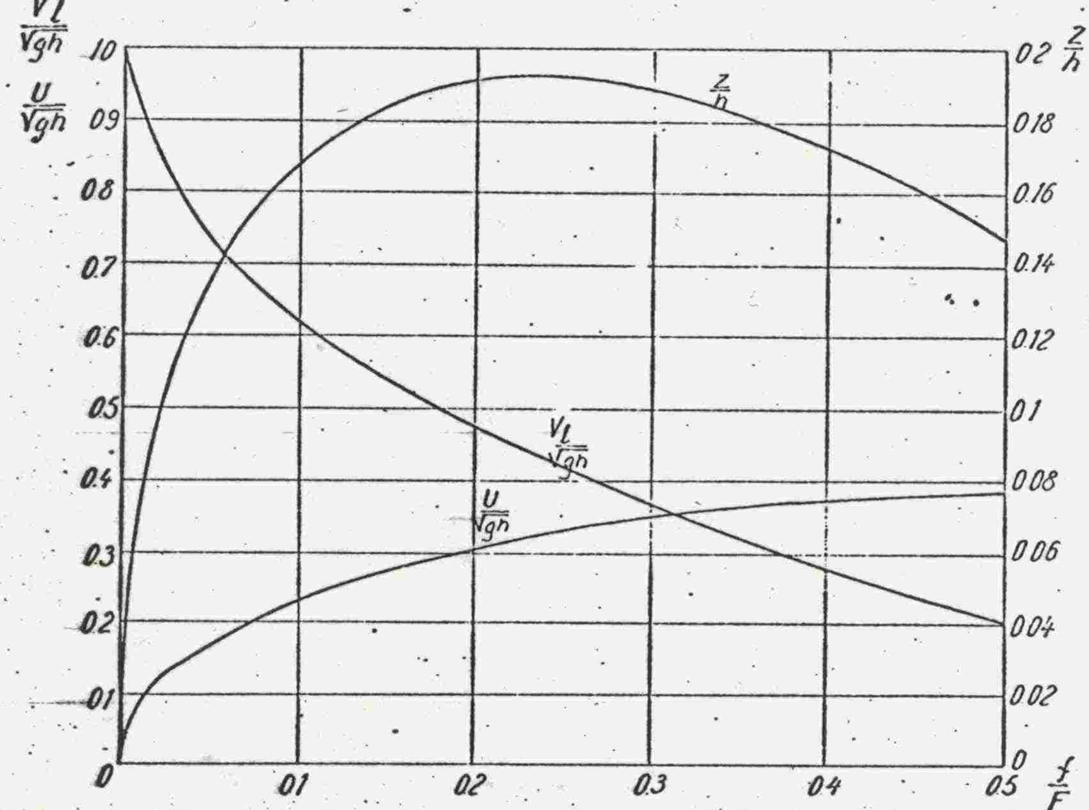
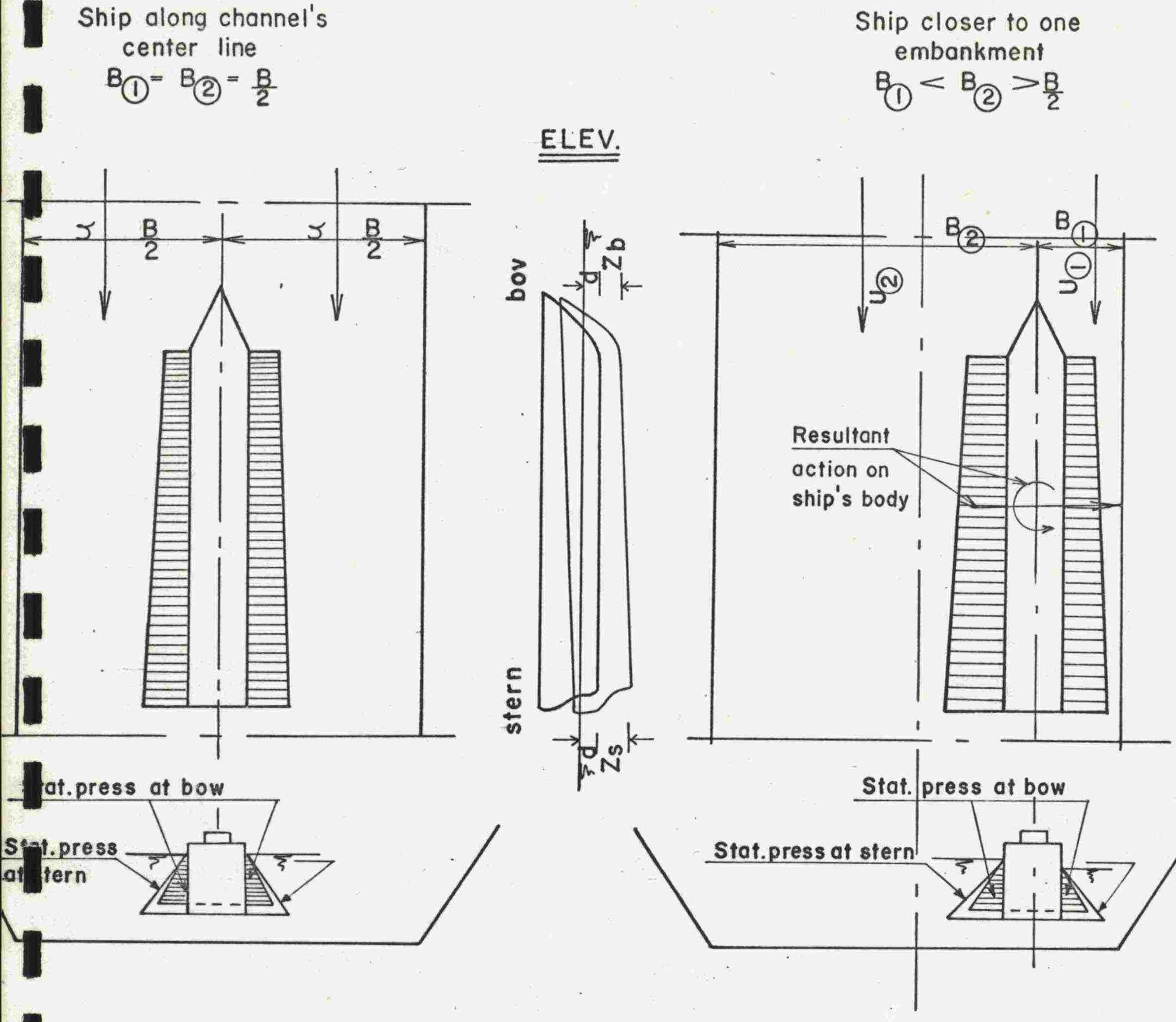


fig. (9)



$u_{①} = u_{②}$

$Z_{①} = Z_{②}$

$(\text{Stat.press})_{①} = (\text{Stat.press})_{②}$

$u_{①} > u_{②}$ and $\propto (\frac{B_2}{B_1} \cdot U)$

$Z_{①} > Z_{②}$

$(\text{Stat.press})_{①} < (\text{Stat.press})_{②}$

Qualitive analysis of ship motion through a waterway of restricted cross section

fig. (10)

Analysis of ship's motion over bends

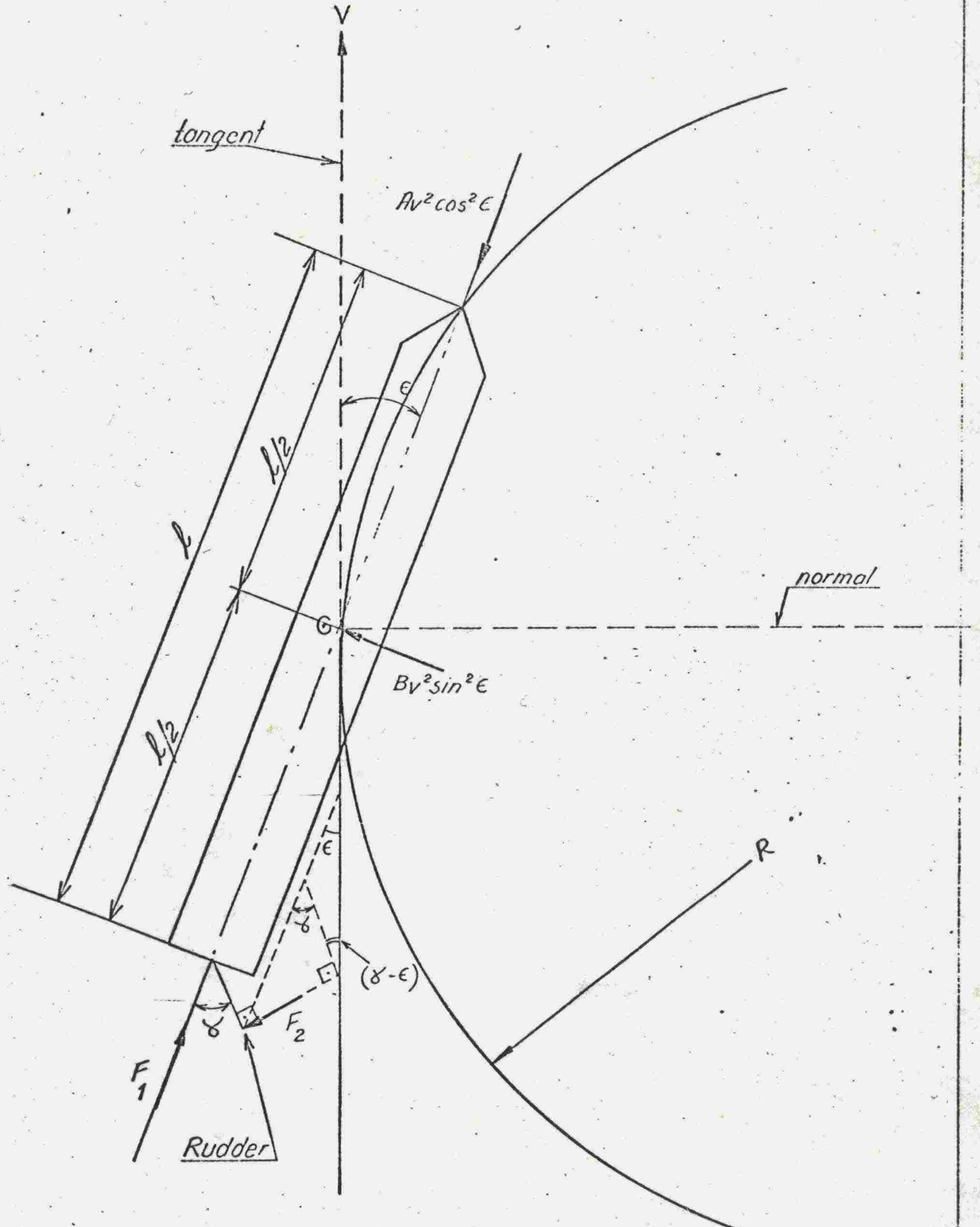
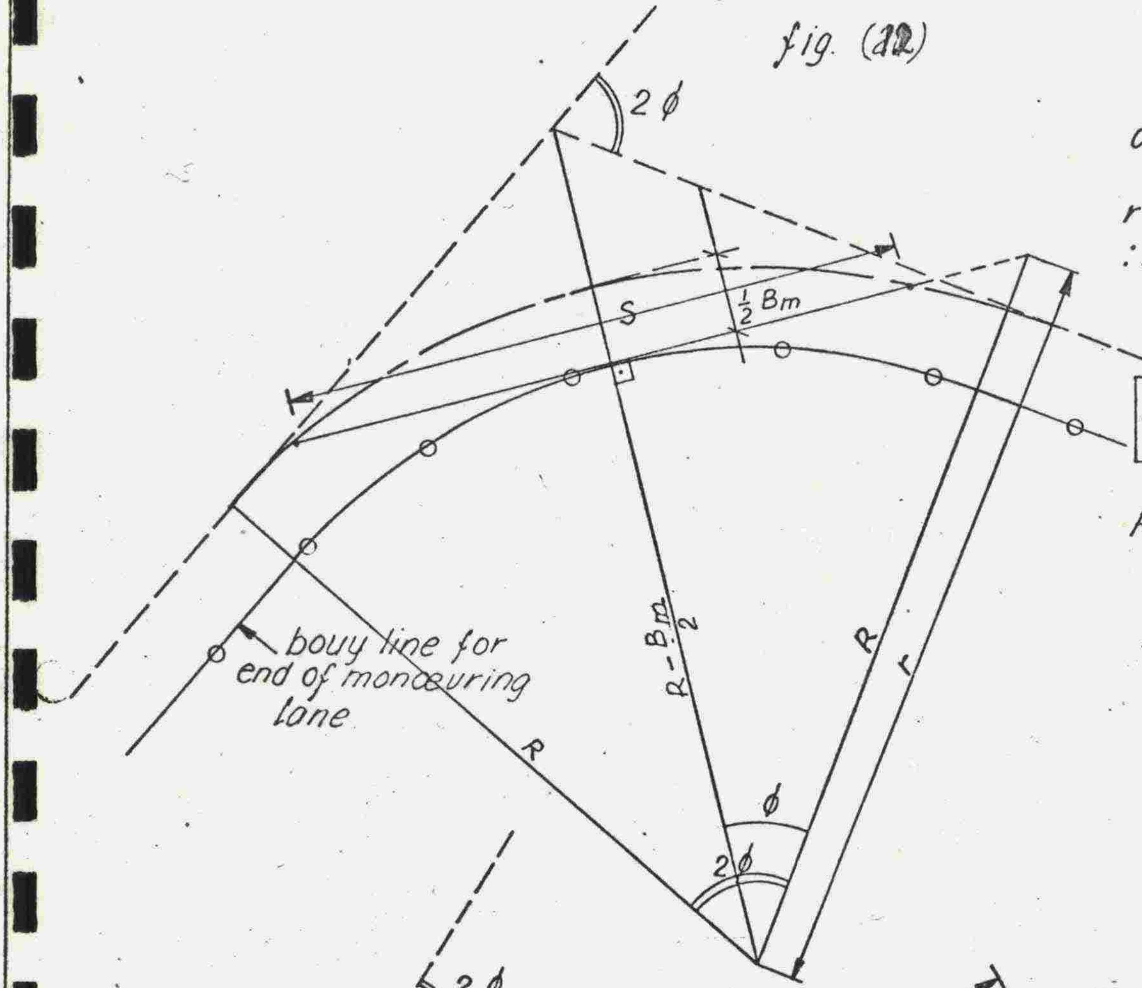


fig. (11)

Bend alignment from point of view of minimum "sight distance"

fig. (12)



$$\cos\phi = \frac{R - \frac{B_m}{2}}{R}$$

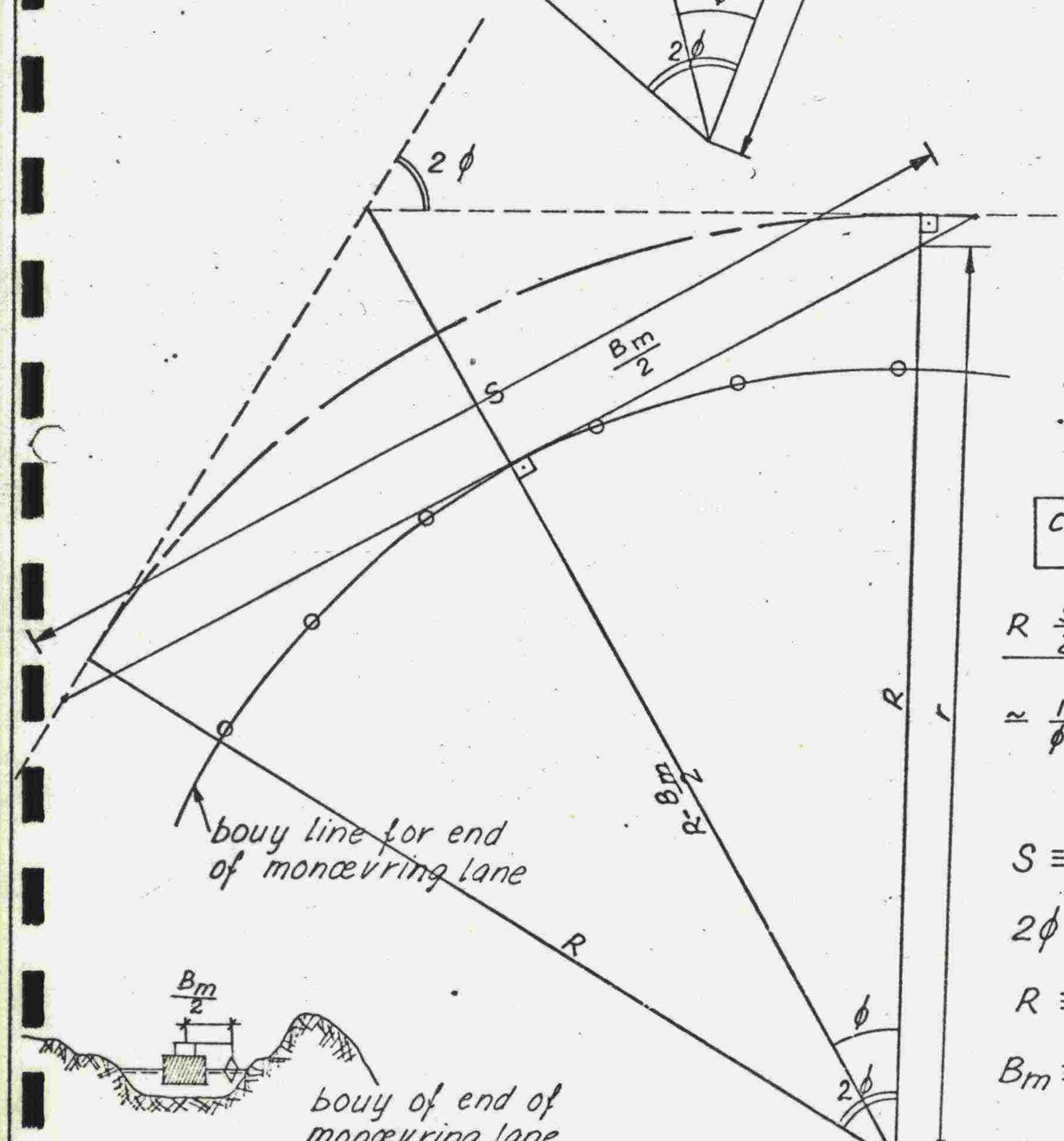
$$r > R$$

$$\therefore \cos\phi < \frac{R - \frac{B_m}{2}}{R}$$

$$\boxed{\therefore \cos\phi < 1 - \frac{B_m}{2R}}$$

$$R = \frac{S^2 + 4B_m^2}{8B_m}$$

$$\simeq \frac{S^2}{8B_m}$$



$$\cos\phi = \frac{R - \frac{B_m}{2}}{r}$$

$$r < R$$

$$\therefore \cos\phi > \frac{R - \frac{B_m}{2}}{R}$$

$$\boxed{\cos\phi > 1 - \frac{B_m}{2R}}$$

$$R \ \frac{\frac{s}{2}\sin\phi - a\cos\phi}{1 - \cos\phi}$$

$$\simeq \frac{1}{\phi}\left(s - \frac{2a}{\phi}\right)$$

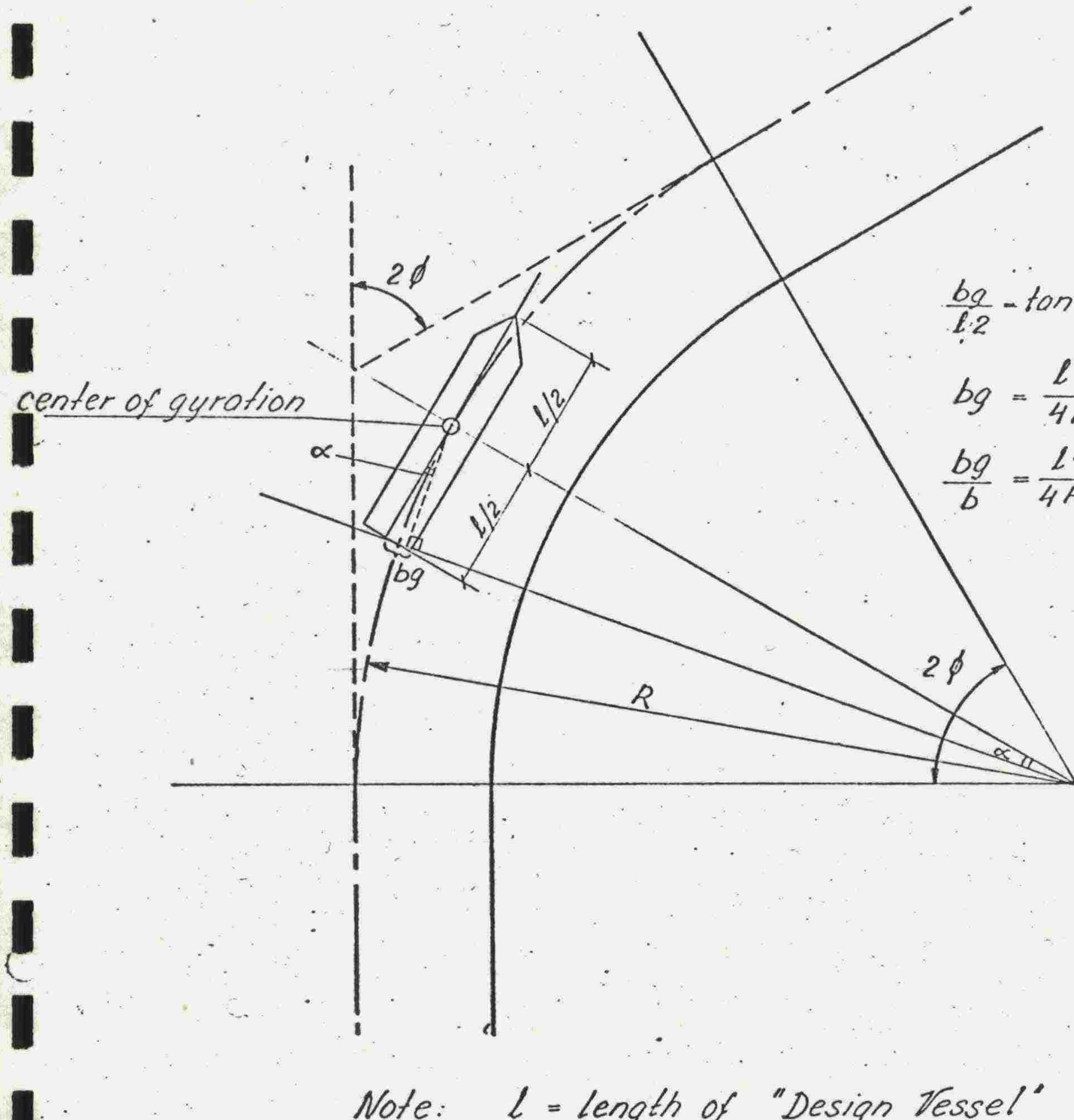
$S \equiv$ Sight distance

$2\phi \equiv$ angle of reflection

$R \equiv$ Radius of curvature

$B_m \equiv$ Monœvring-lane's width

Increase of manœuvring-lane's width, bg, in curved course, due to gyration of the vessel
(center of gyration assumed to be at mid-length)



$$\frac{bg}{l/2} = \tan\alpha = \frac{l/2}{R}$$

$$bg = \frac{l^2}{4R}$$

$$\frac{bg}{b} = \frac{l^2}{4Rb}$$

Note: l = length of "Design Vessel"

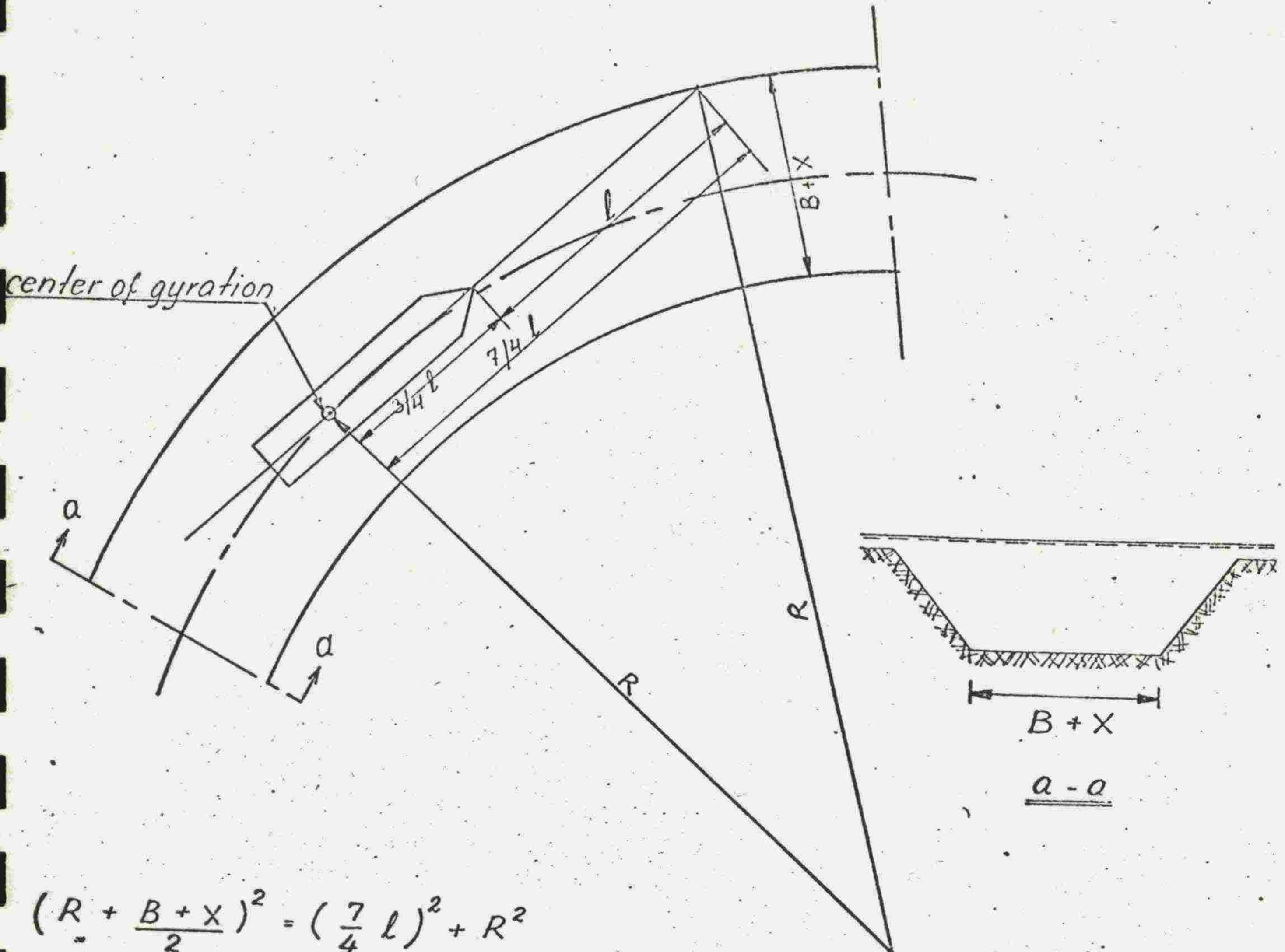
b = Design Vessel's beam

bg = Increase of "Manœuvring-lane" width, due to gyration

R = radius of curvature

fig. (13)

Sucz Canal Practice for dimensioning bends.



$$\left(R + \frac{B+X}{2}\right)^2 = \left(\frac{7}{4}\,l\right)^2 + R^2$$

$$R^2 + R\,(B+X) + \left(\frac{B+X}{4}\right)^2 = \frac{49}{16}\,l^2 + R^2$$

$$\therefore\ R = \frac{1}{B+X}\left[3.06\,l^2 - \left(\frac{B+X}{4}\right)^2\right]$$

R ≡ radius of curvature

l ≡ ship's length

B ≡ width of straight channel

X ≡ increase in width of bend

fig. (14)